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MULTIMEGAWATT BROADBAND MICROWAVE TUBES

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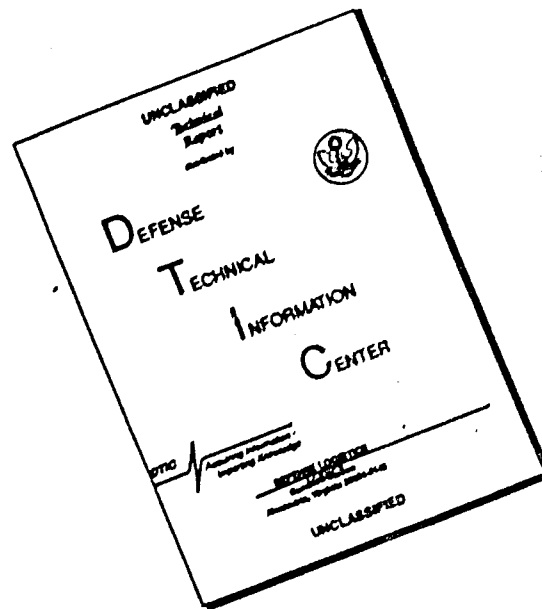
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Project No. 5573, Task No. 557303

J
(Prepared under Contract No. AF30(602)-2575 by Microwave Laboratory,
W.W. Hansen Laboratories of Physics, Stanford University, Stanford,
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FOREWORD

This is Quarterly Status Report No. 10, for the period of 1 February through 30 April 1964. This report describes projects active in the third year of this contract.

At the present time there are six projects, as follows:

1. Centipede TWT
2. Periodic Circuit Studies
3. Oscillation Suppression in TWT's
4. Extended-interaction Klystrons
5. Transverse-wave Studies
6. Nonperiodic Dielectric-lined TWT

The project titled "Oscillation Suppression in TWT's" has been completed. A technical report, "On the Analysis and Suppression of Oscillations in High-power Traveling-wave Tubes," by A. J. Bahr, has been written, which describes all the work on this project. The abstract of this report (RADC-TDR-64-172, June 1964) is presented herein.

The Responsible Investigator for this contract is Professor Marvin Chodorow.

Key words: Traveling Wave Tubes; Microwave Interaction Circuits;
Transverse Wave Studies.

ABSTRACTS

1. CENTIPEDE TWT

The centipede circuit has been adapted for use on the electron stick in such a manner that the amplitude and phase of the growing wave along the beam-circuit interaction length can be measured. The results of this study will be of utmost value in optimizing the many parameters affecting the beam-circuit interaction. Current results of theory and experiment are presented.

2. PERIODIC CIRCUIT STUDIES

A. HIGH-POWER TWT CIRCUIT STUDIES

Modification of existing circuits and new circuits for high-power TWT's are investigated in order to improve the bandwidth, impedance and stability characteristics of this class of tubes. A new circuit is considered which has over two-to-one bandwidth (2500 to 5500 Gc). The results of a modification of the centipede circuit are also presented. Both of these studies are now completed.

B. PERIODIC DIELECTRIC H-MODE GUIDE

Evaluation of the unshielded periodic array of small dielectric resonators as a new positive-dispersion slow-wave structure providing an axial H field is complete. The predicted propagation characteristics were confirmed by measurements on an array of rutile disks, but the data are universally applicable. A very large choice of bandwidths is obtainable accordingly, as the array spacing is very small or very great. A novel distributed ferrite frequency multiplier is proposed.

3. OSCILLATION SUPPRESSION IN TWT'S

The electron stick has been used to evaluate methods of improving the stability characteristics of high-power TWT's. Of particular interest are the pulse-edge (π -point) oscillations. The technique applied to this problem is that of selectively coupling the periodic centipede structure to an external, lossless, uniform guide and comparing the results to those obtained when the external attenuating region is nonpropagating. All the work on this project has been completed, and a complete, comprehensive report has been written. The abstract of this report* is given in Part 3.

* RADC-TDR-64-172, June 1964.

4. EXTENDED-INTERACTION KLYSTRONS

Assembly of the experimental three-cavity tube has been completed, and beam tests on the electron stick are in progress.

5. TRANSVERSE-WAVE STUDIES

Investigation of transverse-wave propagation on accelerated streams is continuing. A technical report describing the results is being prepared.

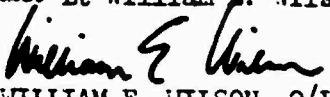
6. NONPERIODIC DIELECTRIC TRAVELING-WAVE TUBES

This project, concerned with nonperiodic extra-high-power S-band tubes based on rf structures that are simply uniform sleeves of dielectric inside a metal shell, has been discontinued. Some recommendations will be set down for the record, as the principle behind these tubes remains promising, provided a beam-tunnel lining other than a helix can be developed.

PUBLICATION REVIEW

This report has been reviewed and is approved. For further technical information on this project, contact Lt William E. Wilson, EMATE, Ext 22224.

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I. OBJECTIVES OF THE CONTRACT

There are several objectives for this contract. One general objective is to conduct theoretical and experimental investigations of microwave tubes with a view toward the development of tubes capable of at least 10 megawatts of peak power, average power approaching 50 kilowatts, bandwidths approaching 30 percent, gains of 35 db, and efficiencies of 40 percent. Another objective includes the investigation of the direct coupling of rf energy onto a plasma and vice versa, and of methods of producing plasmas with high density and lower radial density variations. Another objective is to make a theoretical analysis of the thick beam transverse-wave amplifier and then to conduct an experimental investigation of a dc pumped transverse-wave amplifier, employing the results of the theoretical work.

II. SUMMARY AND ANALYSIS OF THE WORK

1. CENTIPEDE TWT

(D. K. Winslow,* T. Reeder)

A. INTRODUCTION

The objective of this project is to study the electron beam - slow wave circuit interaction in a high-power traveling-wave tube. The centipede slow wave circuit, a coupled cavity structure, will be used in this study. In particular, the centipede has been chosen because it has proven to be one of the most satisfactory slow waveguides for a high-power TWT. The method of investigation will be to measure the amplitude and phase of the fields in each centipede cavity while the centipede is mounted on the electron stick and is being operated as a TWT. Measurements over a particular region will be possible, such as at a sever and in the output section of the tube. The results of this study will be of utmost value in optimizing the many parameters affecting the beam-circuit interaction.

B. DISCUSSION

The fields inside each centipede cavity are sampled by a small, movable loop probe which is coupled to the fields by small slots located between the feet of adjacent centipede loops, as shown in Fig. 1. The probe can be moved over the entire length of the centipede structure, and it can be precisely positioned over a particular cavity slot. The size of the slots was adjusted to provide about one-tenth of a milliwatt of probe output when one kilowatt is applied at the centipede input coupler. Still, the slots are small enough that the power radiated out of one slot does not interfere with the measurement at the next slot.

* Project supervisor

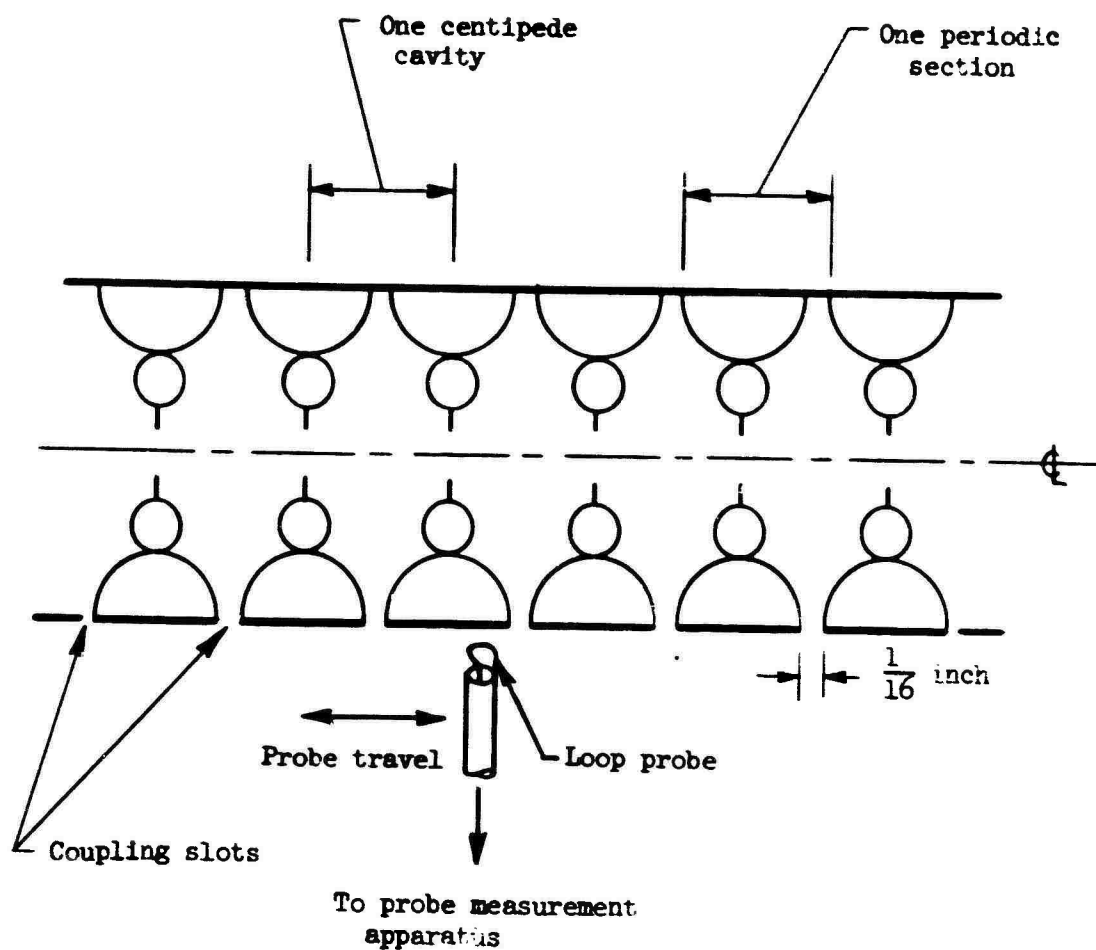


FIG. 1--Cross-sectional view of the centipede structure showing field probe and coupling slot location.

The amplitude of the fields in each cavity is measured by positioning the movable probe over the coupling slot in a particular cavity, the probe output being measured by a square-law crystal detector. The detector voltage output is thus proportional to the amplitude squared of the cavity fields. The measurement of phase of one cavity to another is accomplished by mixing the movable probe output with a reference sample of the centipede input power in a slotted waveguide. The relative phase of the fields in each cavity is then related to the shift of the null points in the slotted waveguide as the probe is moved from cavity to cavity. This method has been described in some detail in an earlier report.⁽¹⁾

During the past quarter the amplitude and phase of the centipede TWT have been measured under small-signal conditions. Although it was necessary to add 10 to 15 db of distributed loss to the centipede in order to stop parasitic electron stick oscillations, gains of up to 15 to 20 db were recorded. The centipede circuit for these measurements consisted of 16 periodic sections terminated by a sever.

The phase measurements were most interesting, and to the author's knowledge, the present experiments on the centipede are the first measurements of phase vs interaction length ever made for a TWT. Figure 2 shows a typical plot of phase vs centipede interaction length. Note that the phase delay of the fields in each centipede cavity has been measured with respect to the first cavity after the input coupler. Since identical centipede sections were used, the phase shift from one cavity to the next under cold conditions must be the same anywhere in the tube. This fact was demonstrated experimentally and can be seen in Fig. 2. In fact, the phase data with no beam is so uniform that a straight line can be quite accurately drawn through the data. The slope of this line is simply the phase shift per section of the centipede circuit. When the beam is turned on, the phase along the tube length changes. In the first few cavities the phases change rapidly up and down, perhaps indicating that several waves, growing and decaying, are being launched in the cavities by the beam. However, the phase again becomes uniform in the last few cavities before the sever-load.

⁽¹⁾Quarterly Status Report No. 7 for Contract AF 30(602)-2575, Microwave Laboratory Report No. 1080, Stanford University (September 1963).

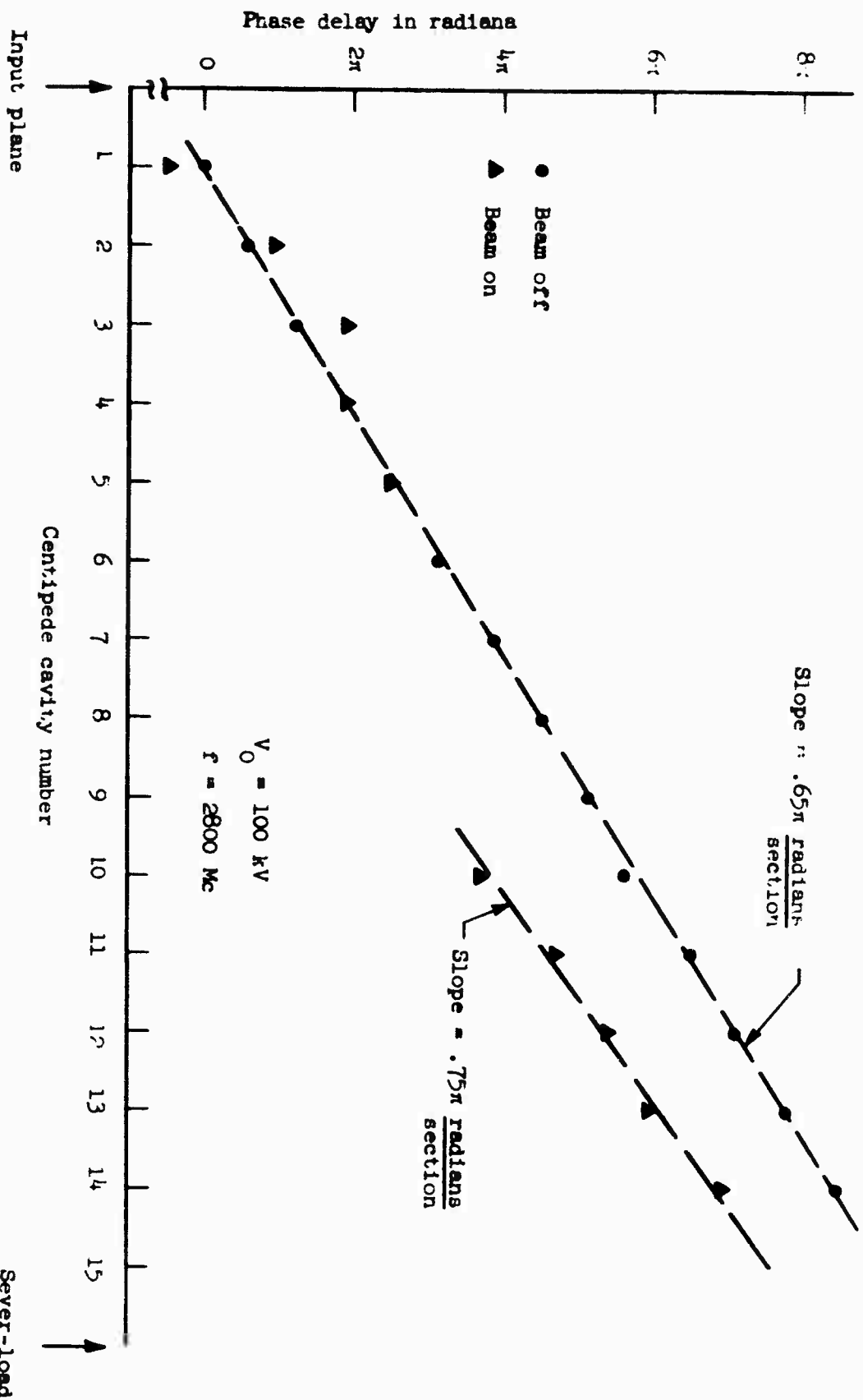


FIG. 2--Phase delay versus distance for the centipede TWT.

thus showing that a single growing wave is dominant. Again a straight line may be drawn through the data to estimate the phase shift per section of this growing wave. Phase data like that in Fig. 2 has been recorded over most of the centipede passband.

If one plots the frequency of measurement vs the phase shift per section as determined from phase data like that of Fig. 2, the result gives an ω - β diagram for both "beam on" and "beam off" conditions. Figure 3 shows experimental ω - β data which was determined from many curves like Fig. 2. The "beam off" or cold data shown in Fig. 3 demonstrates that the experimental method is capable of high accuracy. Furthermore, with the beam on, the ω - β data shifts due to the coupling of the slow space-charge wave and the forward centipede wave. Thus, the fact that the phase has shifted to a position closer to the slow space-charge wave in Fig. 3 is very reasonable. The "beam on" data show more scatter than the "beam off" data since the effect of reflections is much greater when the beam is on.

The rf power or the square of the centipede field amplitude in each cavity was measured over the entire passband of the centipede. A typical measurement of relative power vs distance along the centipede interaction length is shown in Fig. 4. Since the field amplitude squared is proportional to the axial power flowing in the centipede circuit, it is convenient to plot the amplitude squared data in db. All the data have been normalized so that the power at cavity number one with the beam off is zero db. Figure 4 shows that the power increased 12.5 db at cavity one when the beam was turned on. With the beam off, the power is attenuated with distance at about 0.9 db/section. Note that there is some scatter of the data around the straight line approximation of this attenuation. This scatter is caused by nonuniform coupling of the fields to the traveling field probe as was discussed in a previous report.⁽¹⁾ Figure 4 also shows the growing wave phenomenon in the last few cavities, the asymptotic gain being about 0.8 db/section. The data at other frequencies were examined to determine the asymptotic gain and the "beam off" circuit attenuation as in Fig. 4. The results are presented in Fig. 5.

⁽¹⁾ Second Annual Report for Contract AF 30(602)-2575, Microwave Laboratory Report No. 1116, Stanford University (October 1963), pp. 9-12.

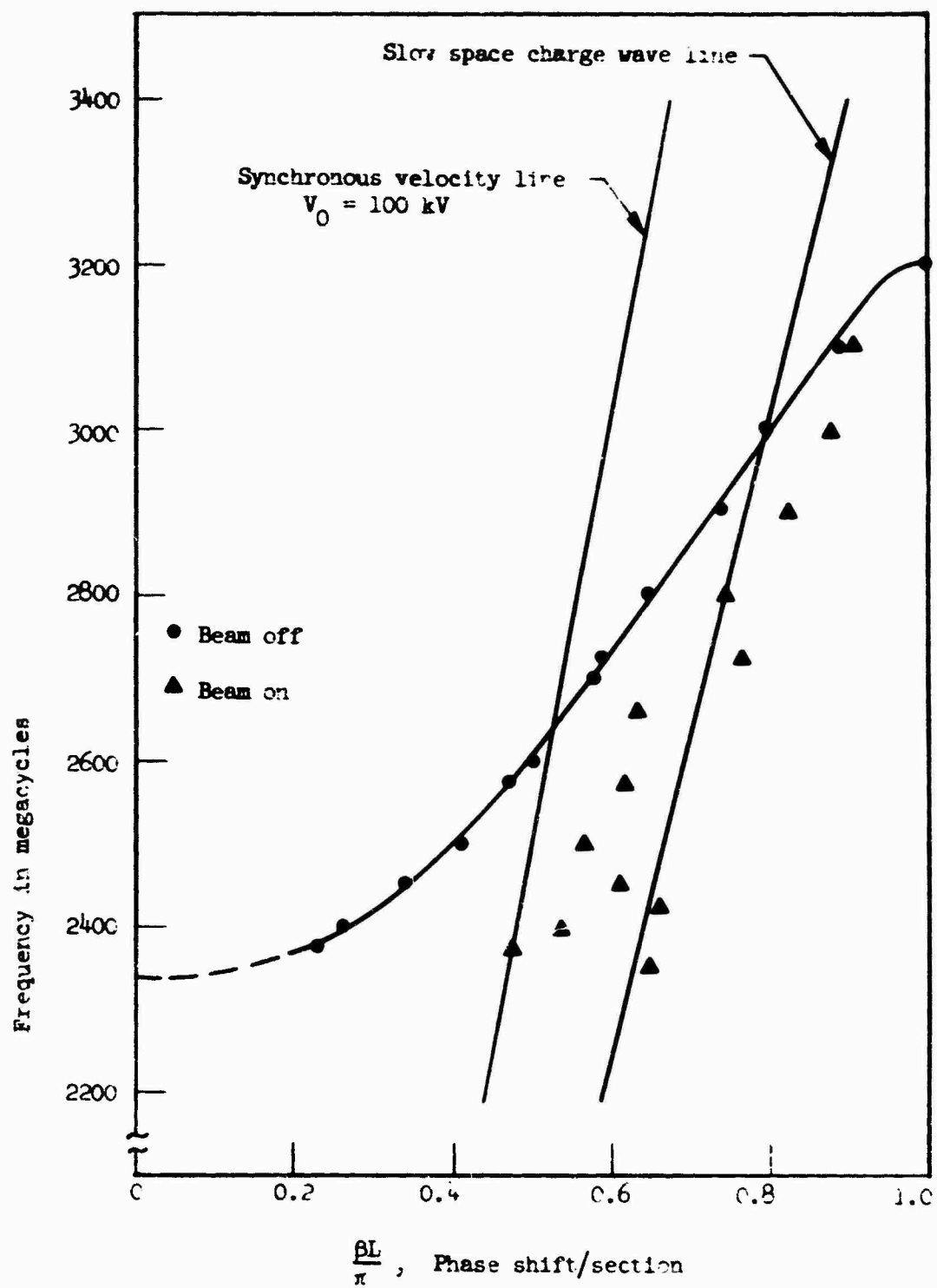


FIG. 3-- ω - β diagram for the centipede IWT.

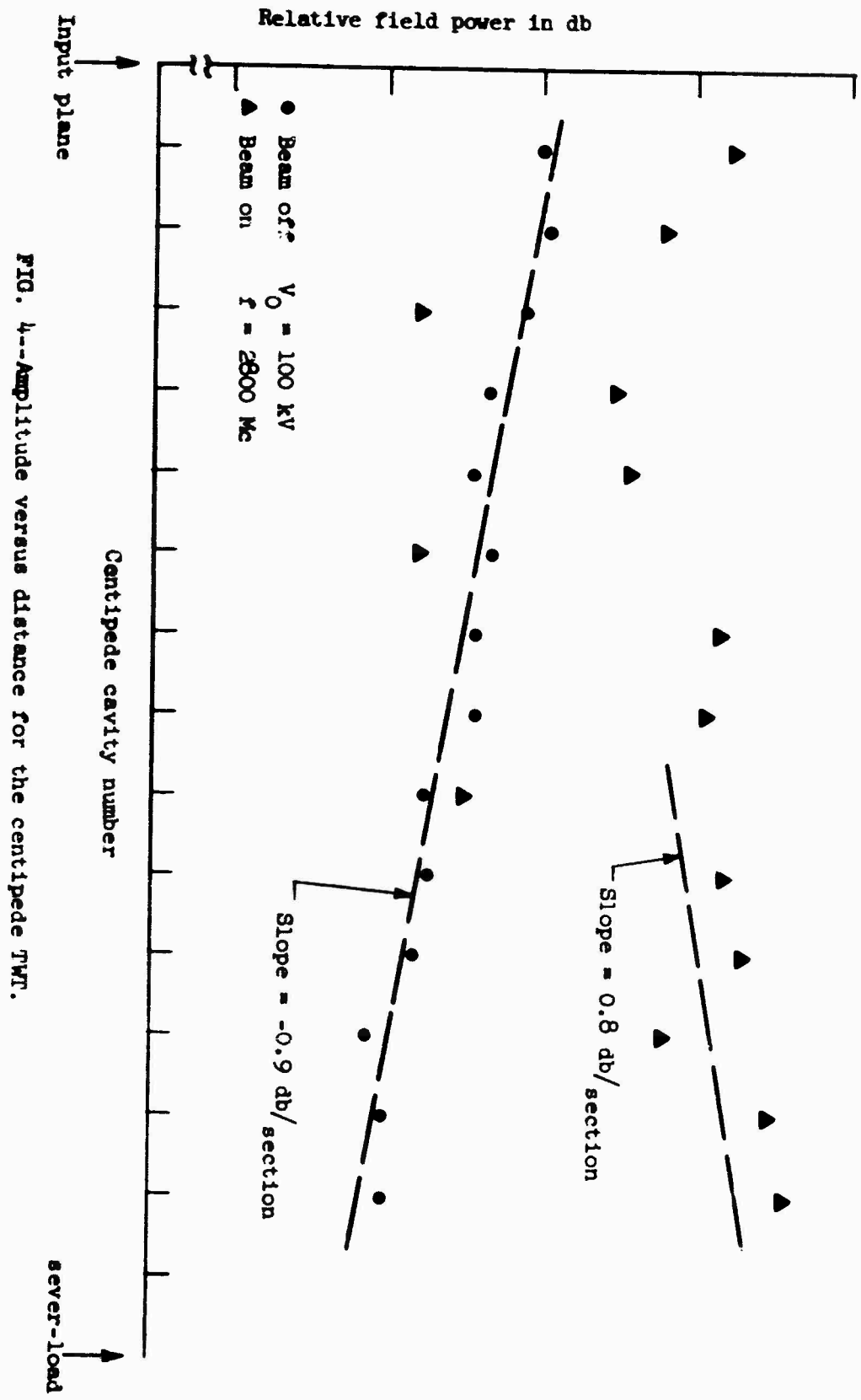


FIG. 4--Amplitude versus distance for the centipede TWT.

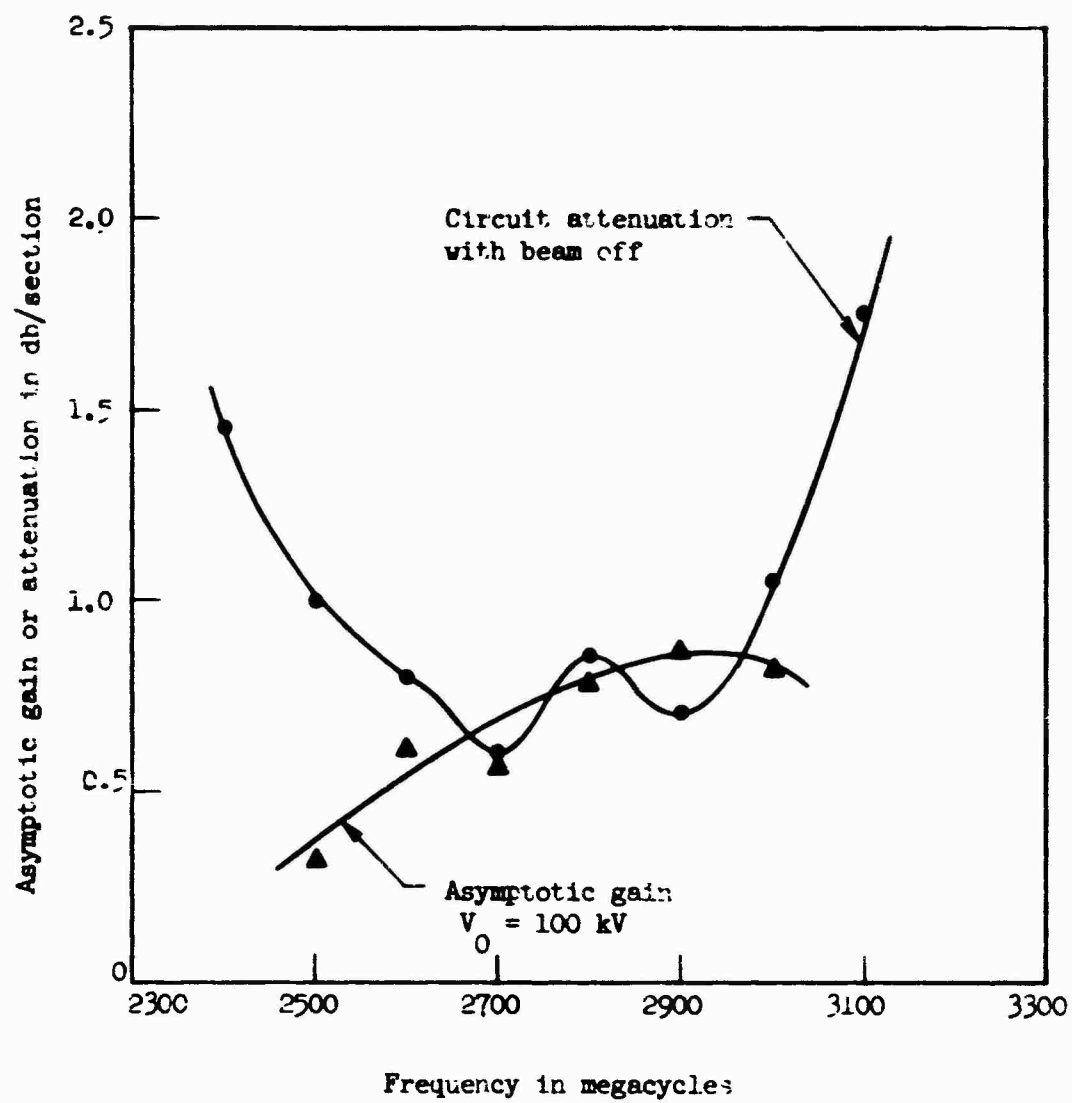


FIG. 5--TWT gain and circuit attenuation.

In summary, it should be said that the centipede TWT operated on the electron stick performs quite well despite the rather high cold circuit attenuation needed to suppress stick oscillations. It has been possible to measure phase and amplitude vs interaction length at beam voltages up to 100 kv. During all of these measurements, the TWT operation was stable. No pulse edge or structure oscillations were observed.

C. FUTURE PLANS

Work is continuing on a small-signal theory for the centipede that includes the effect of two circuit and two beam waves. This theory, which exhibits four waves rather than the usual three, is derived using an accurate equivalent circuit for the centipede and a wide gap ballistic model of the beam. A detailed description of the equivalent circuit is found in another report.⁽¹⁾ The beam interaction with the centipede circuit field assumes that each centipede cavity looks like a long transit angle planar gap, and space-charge forces are included. At present this theory is being used to calculate a "beam on" ω - β diagram which should verify the experimental data shown in Fig. 3. Thereafter, a calculation of field amplitude and phase vs interaction will be done, taking into account the boundary conditions of the beam and circuit.

⁽¹⁾Quarterly Status Report No. 6 for Contract AF 30(602)-2575, Microwave Laboratory Report No. 1037, Stanford University (May 1963).

2. PERIODIC CIRCUIT STUDIES

(D. K. Winslow, ^{*} T. Fukunaga, A. Karp, R. M. Malbor.)

A. HIGH-POWER TWT CIRCUIT STUDIES

(1) Introduction

The objective of this part of the program is to investigate the properties of new high-power TWT circuits and modifications of existing circuits in order to improve their performance characteristics. During this investigation, the characteristics of the long-slot structure have been rather radically modified by the use of straps which extend the length of the structure and are attached to each disk at the center of each slot. The two most remarkable features of this circuit are the large bandwidth (2500 to 5500 Mc/s) and the apparent confinement of the lower slot mode to the slot region such that the impedance of the lower mode on the tube axis is very small. The other structure of interest is a modified loop-coupled centipede in which each section consists of loops over half the circumference and the other part a half disk. The structure is composed of these sections, mounted such that the loops are opposite the half disks in adjacent sections, or a 180-degree rotation from section to section. The purpose here is to introduce a larger frequency separation and/or reduced interaction impedance of interfering modes while maintaining or improving the bandwidth and impedance characteristics of the operating mode. This part of the program has now been completed.

(2) Discussion

(a) Long-slot Structure Modifications and a New Related Structure

This work has resulted in a structure with over a two-to-one bandwidth in the forward-wave operating mode. The structure consists of slot-coupled cavities with no fins and with a conducting strap extending the length of the structure through the slots and attached to each disk at the inner diameter of the slots. A section view of the new structure is shown in Fig. 6. The dispersion diagram and relative impedance for this structure and, for comparison, the typical long-slot structure are shown in Fig. 7. The different

^{*} Project Supervisor

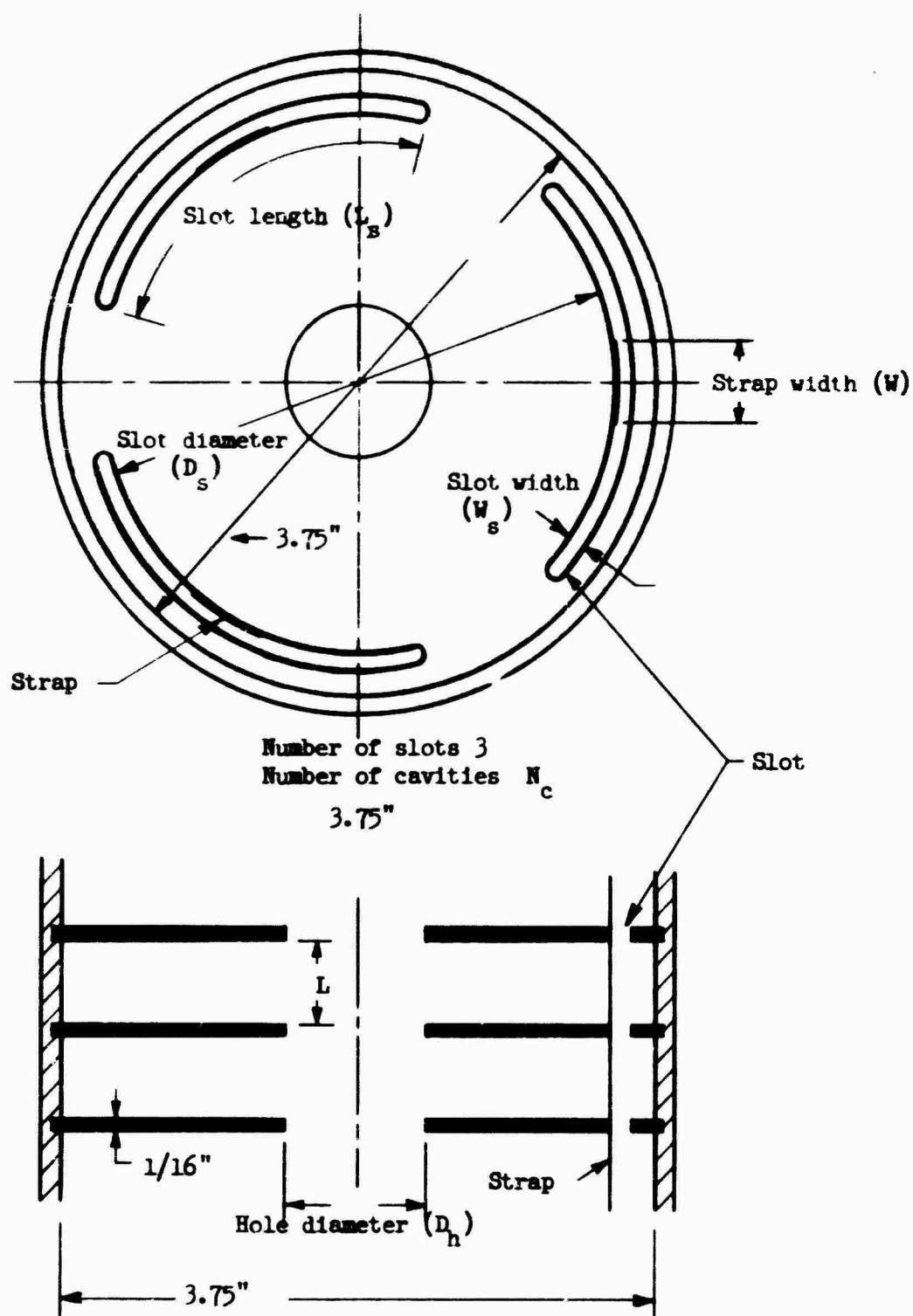


FIG. 6--Diagram of strapped structure.

$$v_p = c$$

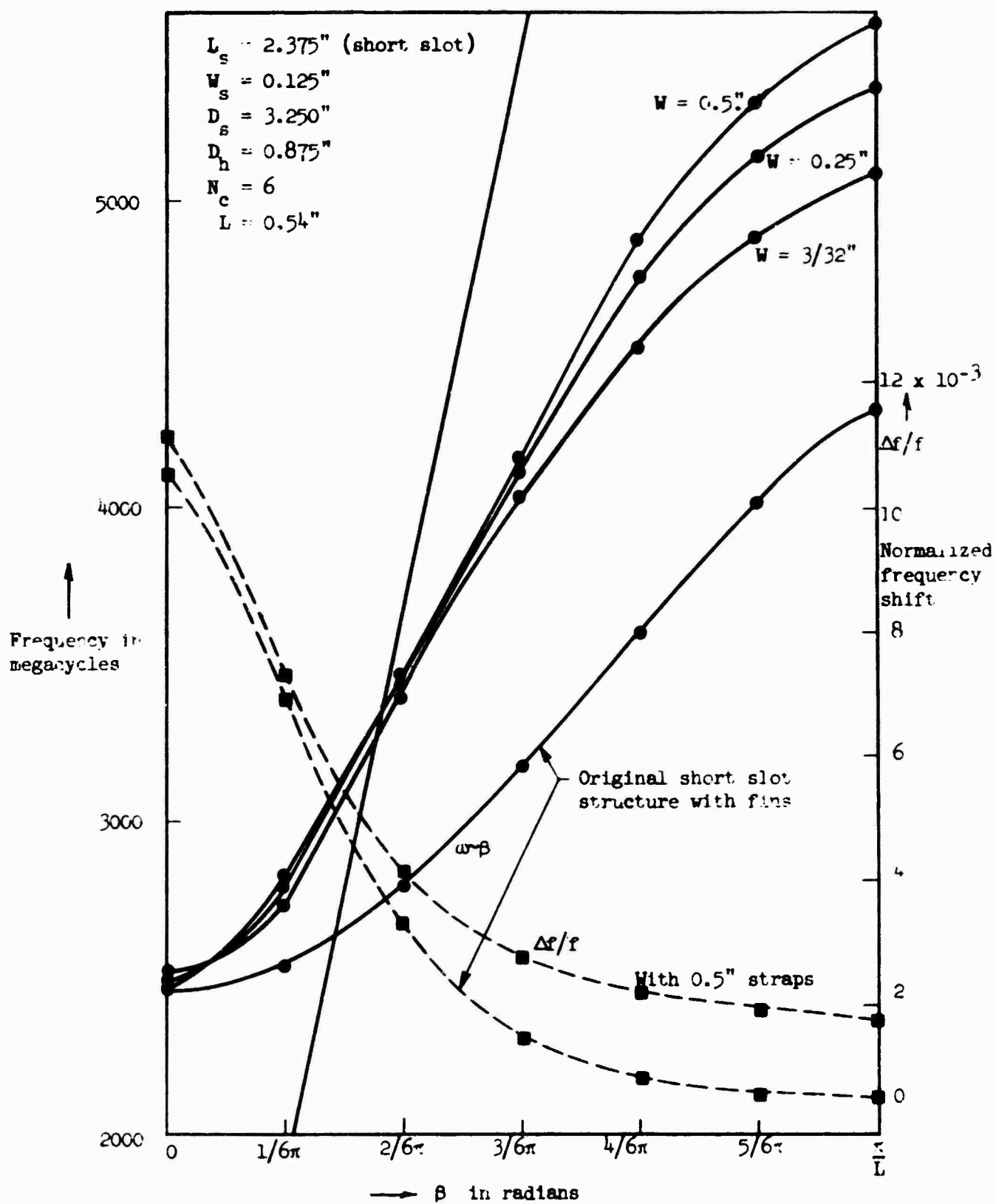


FIG. 7-- $\omega\beta$ and impedance characteristics of strapped structure (short slots).

curves of Fig. 7 are for different strap widths. The relative impedance, $\Delta f/F$, is shown for the one-half-inch strap. A slower structure of length $L = 0.286$ in., is compared to a structure of standard length, $L = 0.540$ in., and is shown in Fig. 8. Part of the decrease in bandwidth of the shorter structure is due to the smaller drift tube hole of the shorter structure, 0.250 in. diameter rather than the standard 0.875 in. diameter. The most remarkable feature of this strapped structure is the large bandwidth, 2500 Mc to 5500 Mc, with an increase in the relative impedance $\Delta f/F$. Part of this, however, is related to the faster phase velocity of the circuit. It is also to be noted that the relative impedance of the lower slot mode has been decreased. This mode is difficult to detect on the axis of the structure. Apparently the fields of this lower loop mode are confined to the region of the straps and slots. This should be an important factor in the complete suppression of this mode.

(b) A Modified Centipede Structure

This section describes a modification of the centipede structure that may have advantages over the present circuit. The purpose is to maintain or improve the bandwidth and impedance characteristics of the operating mode and simultaneously introduce a larger frequency separation and/or reduced interaction impedance of interfering modes.

The centipede structure was modified by inserting semicircular shorting planes in place of half of the loops. Each section was then placed adjacent to each preceding section in forming the structure in a manner such that each succeeding plane was diametrically opposed to the preceding one. Since the normal symmetry of the centipede was destroyed with respect to the plane between adjacent sections, the plane of shorting at the ends had to be placed in the center plane of the loops to preserve symmetry. A schematic representation of the circuits is shown in Fig. 9.

Since the modification of the first structure indicated that the desired characteristics were obtainable at the expense of bandwidth in the operating mode, the modification was extended to three similar centipede structures, each structure differing only in the loop height as shown in Fig. 10. It was hoped that for increased loop height, the bandwidth of

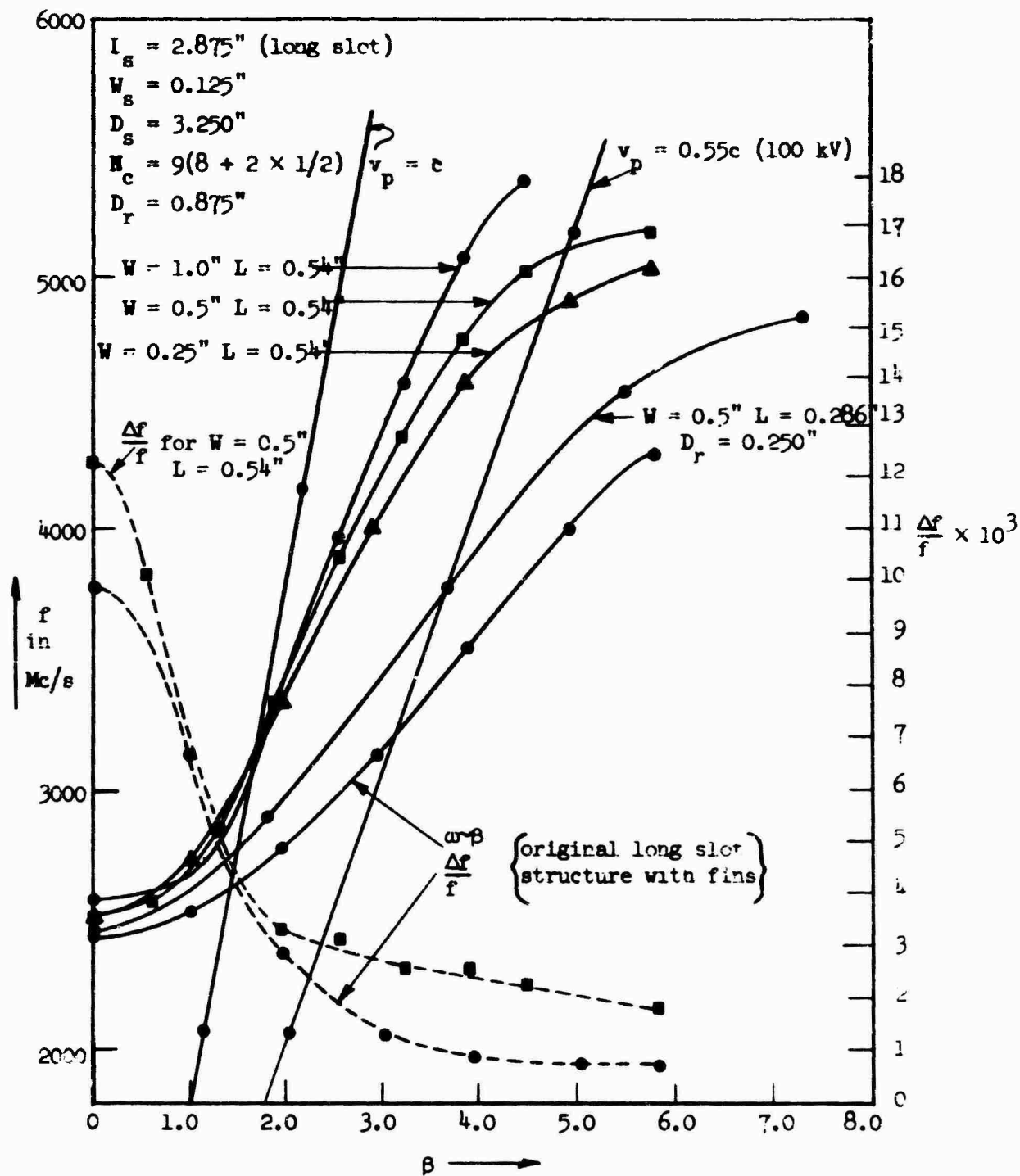


FIG. 8-- ω - β characteristics of strapped structure including a structure of decreased length ($L = 0.286$ inches).

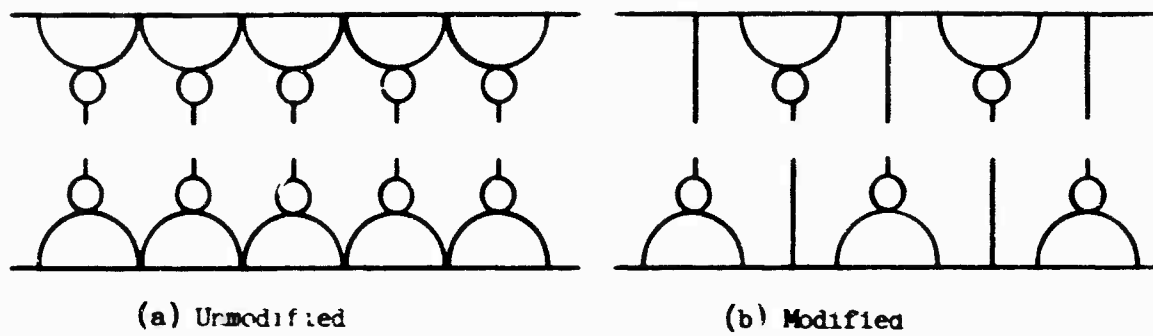


FIG. 9- Schematic representation of circuits.

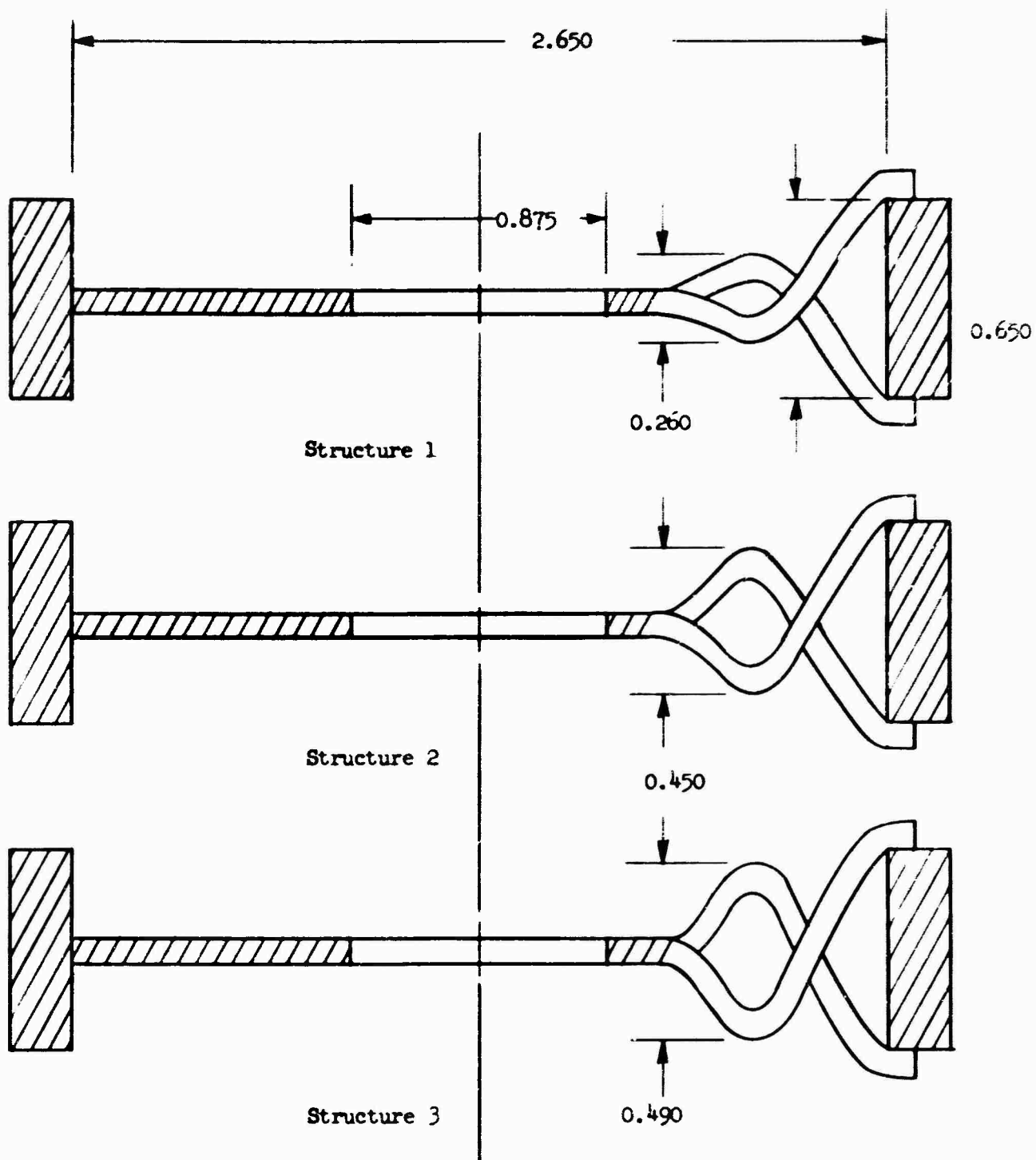


FIG. 10--Section view of the three modified structures tested illustrating loop height.

the fundamental passband would also be increased to compensate for the decrease in number of coupling loops.

It was noted that the bandwidth of the TM_{01} fundamental was decreased in all three structures when the shorting planes were substituted for one-half of the loops. It had been suggested previously that the bandwidth of the TM_{01} fundamental in the centipede structure was proportional to \sqrt{n} , where n is the number of loops, everything else being held constant. In the structures under consideration here, it was found that for the standard centipede structure (structure 2) the ratio of the bandwidths was very close to $\sqrt{2}$ as would be expected. However, as the loop height was decreased, the ratio of the bandwidths increased significantly, and for increased loop height, the ratio decreased.

Before comparing the characteristics of these three structures, it was noted that the loop resonance passband for structure 1 (small loops) was shifted up in frequency more than expected in comparison to the other two structures. A closer investigation of structure 1 revealed that the capacitance developed between the loops at the crossover points was considerably smaller than that developed between the loops of the other structures. If this crossover capacitance is compensated for in structure 1, the resultant dispersion curves are those illustrated in Fig. 11. Figures 12 and 13 compare the $\Delta f/F$ characteristics of the three structures, original and modified.

A comparison of the frequency characteristics as illustrated in Fig. 11 indicates that the modified structures suffered a bandwidth loss in the TM_{01} fundamental passband, but that the stopband in all cases was increased by this modification. Further, the interaction impedance, $\Delta f/F$, shown in Figs. 12 and 13, was significantly increased in the TM_{01} fundamental passband and decreased in the loop resonance passband. The comparison of structures 1 and 2 indicates that the increase in loop height tends to increase the bandwidth in the fundamental passband; however, when this is extended to structure 3 with still larger loops, the fundamental passband retains the same bandwidth but is shifted down in frequency.

In conclusion, it is to be noted that the modification had the desirable effects of increasing the stopband, increasing the interaction

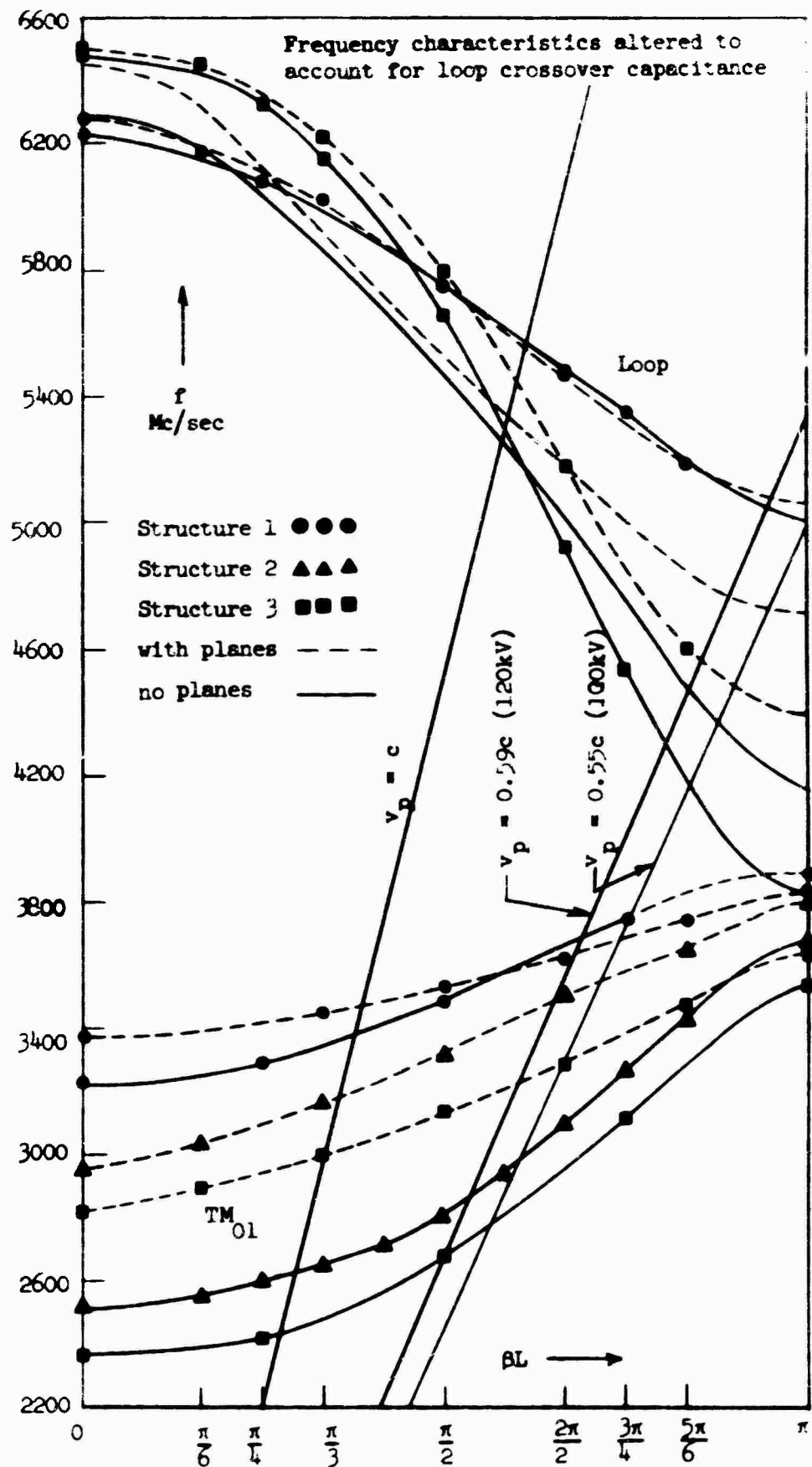


FIG. 11--A comparison of frequency characteristics of compensated structure 1 with structures 2 and 3.

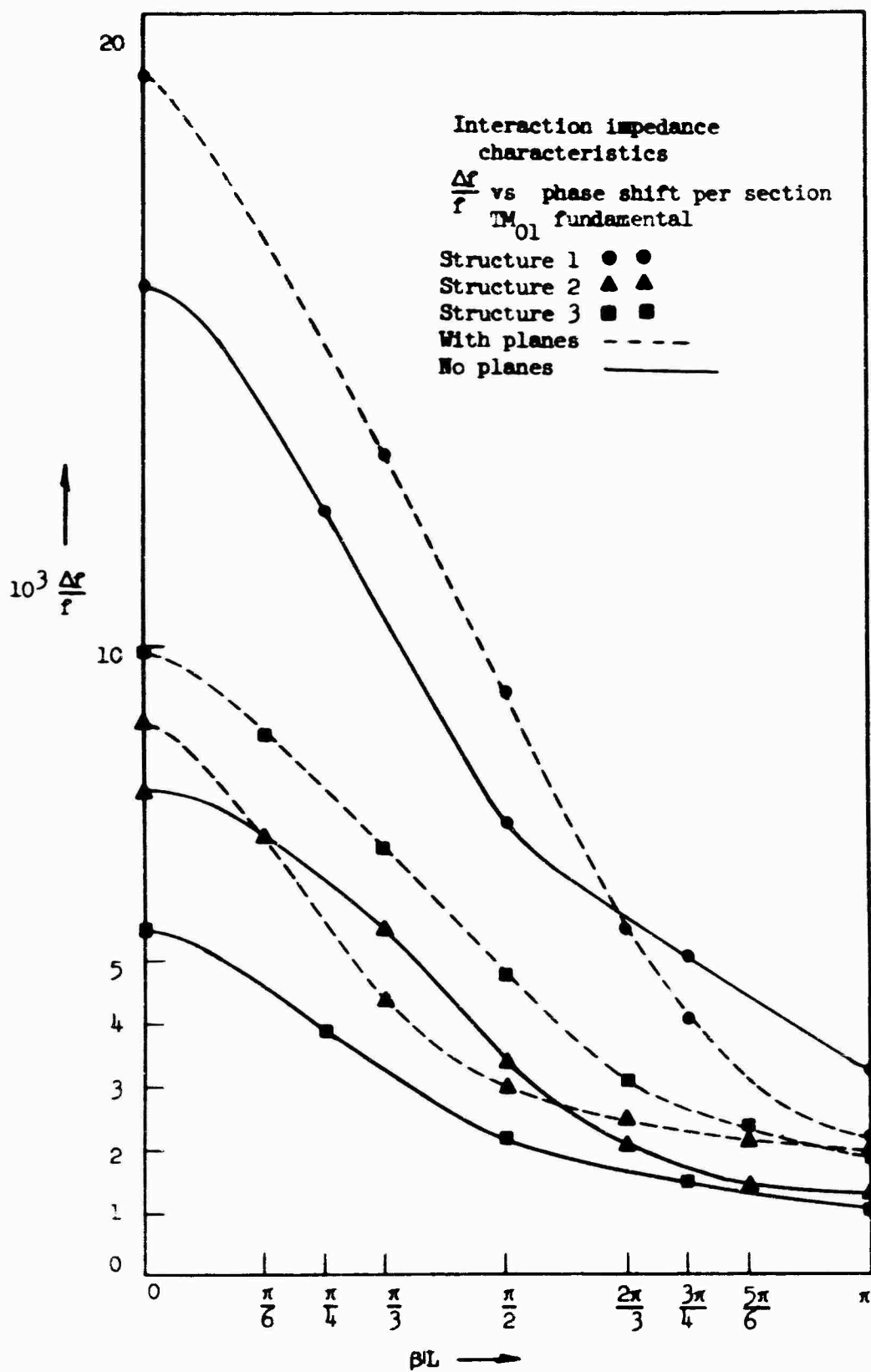


FIG. 12--A comparison of interaction impedance characteristics for structures 1, 2, 3.

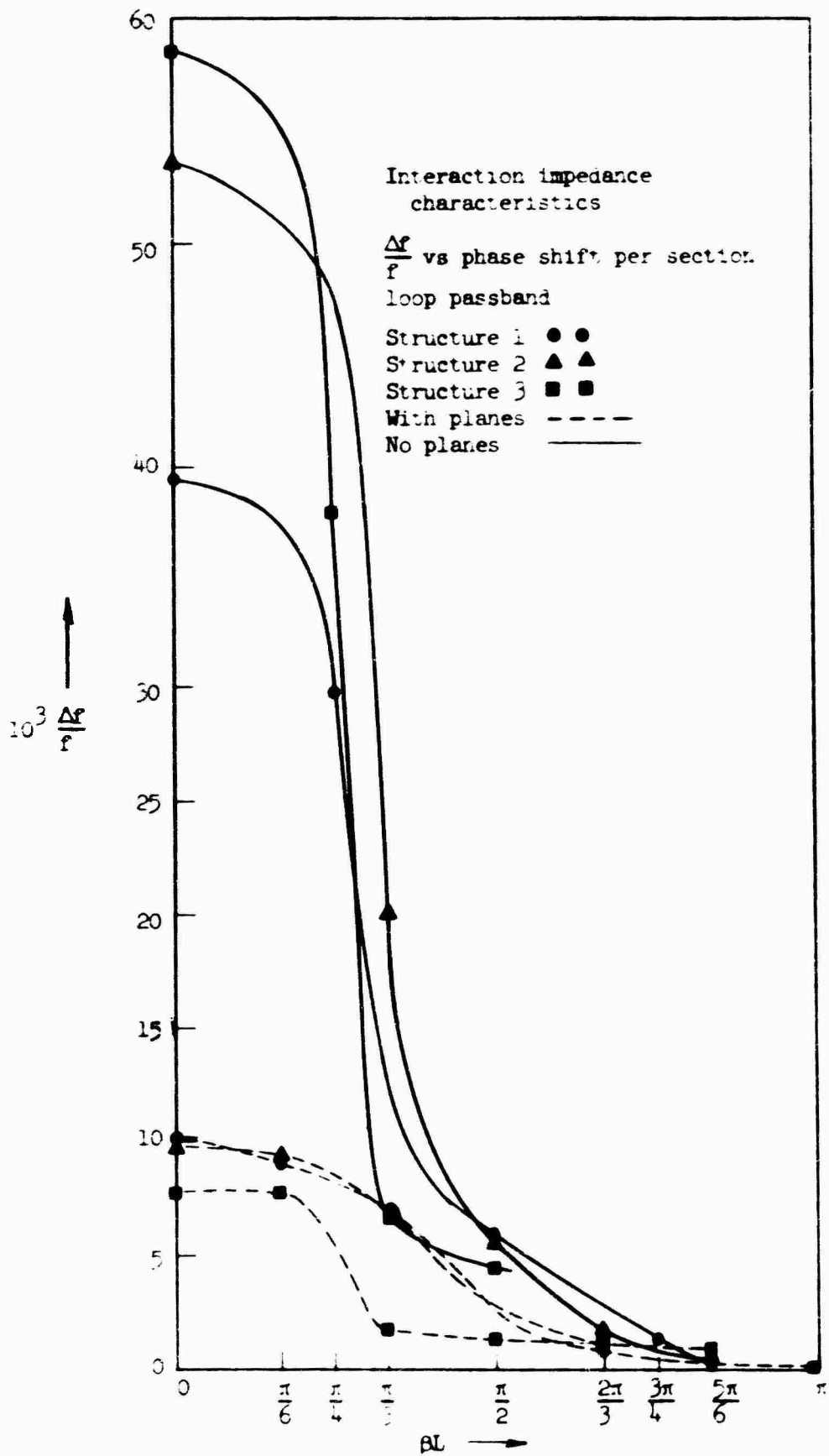


FIG.13--A comparison of interaction impedance characteristics for structures 1, 2 and 3.

impedance $\Delta f/F$ in the fundamental passband while decreasing it in the loop resonance passband. The undesirable effect was the decrease in bandwidth in the fundamental passband. Therefore, the optimum structure would probably be the modified structure 2 which embodies all of the desirable characteristics with only a small percentage decrease in bandwidth of the operating passband. This concludes the high power TWT investigations of this modified centipede circuit.

B. PERIODIC DIELECTRIC H-MODE GUIDE

(A. Karp)

The understanding and evaluation of this new concept in periodic slow-wave structures is essentially complete. The circuit has the form of an array of small, high-Q, high- ϵ' (titanate) dielectric resonators in free space (or supported by material of relatively low ϵ') coupled by the H fields external to them (Fig. 14). Since the coupling generally occurs at some distance from the resonators, the exact shape and orientation of the individual resonator is of small consequence; the parameters determining the dispersion of the structure, to the first order, are merely the spacing (L), and the resonant frequency (f_{00}) of an individual resonator in isolation. The thin disk is a preferred shape, however, because of its circular symmetry and because its lowest resonance frequency (which is taken as f_{00}) is well removed from the many higher frequency resonances a high- ϵ' dielectric volume exhibits. A hole in the center of the disk, yielding a ring, is often useful. Though not essential, it is usually convenient to orient the disks with their axes of symmetry along the axis of the array and to similarly align the crystalline C axis of the material when it is anisotropic (e.g., rutile).

The field configuration of the wave propagating in this medium is essentially TE_{01} . Shielding is optional at all frequencies for which the phase velocity is less than C ; in the infinitely long array, conductors of any kind are assumed absent from the vicinity of the array.

The predicted propagation characteristics of the array were confirmed for many values of L by tests on arrays containing oriented single-crystal rutile disks $1/2$ inch diam. \times $1/8$ inch thick ($f_{00} = 3250$ Mc/s; $Q_0 \sim 10,000$),

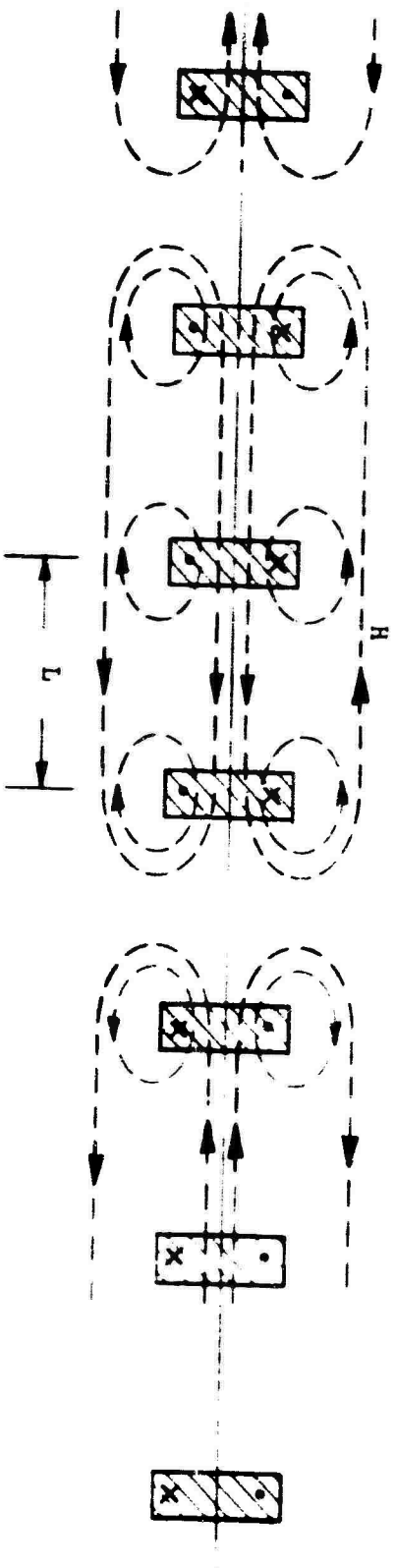


FIG. 14--Periodic array of dielectric resonators in an H-mode slow-wave structure. (Fields are sketched for the condition $\beta = \pi/3L$.)

mounted on plexiglas spiders. Since the effects of the shape of the unit resonator are of second order, these data are universal to the first order, and can be scaled to apply to any array in terms of the dimensionless parameter $f_{\infty} L/C$. To measure the propagation characteristic for a given L , the appropriate procedure would be to observe the $n + 1$ resonances of a finite length of array of n units bounded axially by magnetic mirrors. In the absence of magnetic mirrors, careful interpretation of the n resonances obtainable with the finite array bounded axially (but not radially) by electric mirrors (conducting planes) is adequate, although the lower cutoff condition $\beta = 0$ is not revealed. For example, with conducting planes normal to the axis at a distance of $L/2$ from each end element, and with small coupling loops poking through these end planes, the resonances observed correspond to $\eta\beta L/\pi = 1, 2, 3, \dots, n$, in order of increasing frequency. Due to the ease of varying n and L in the test configuration, multiple checks of data points were possible. Propagation characteristics (which are approximately universal, as discussed) are plotted in Figs. 15 (ω vs βL) and 16 (ω vs β), where comparison with propagation in a nonperiodic rutile rod (i.e., the disks touch) and an infinite rutile medium are possible. (Regions of phase velocity close to C and greater are omitted, as the then necessary shield has some influence.) As predicted, the dispersion is positive ("forward wave") and the passband is roughly centered at the resonance frequency of the unit element. As L decreases, bandwidth increases.

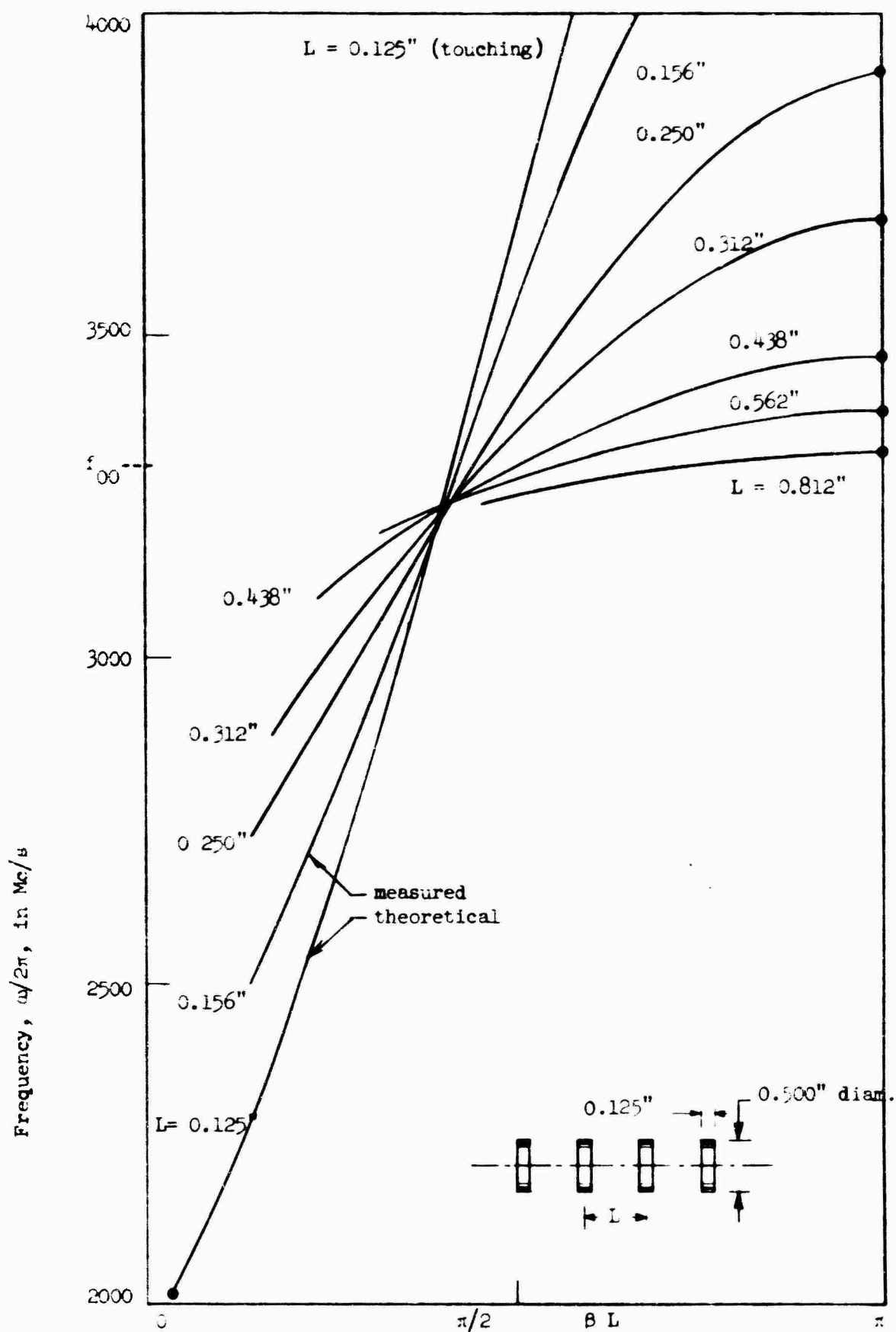


FIG.15-- ω - β diagram of slow-wave propagation on an unshielded infinite array of rutile disks (c-axis longitudinal) for various spacings.

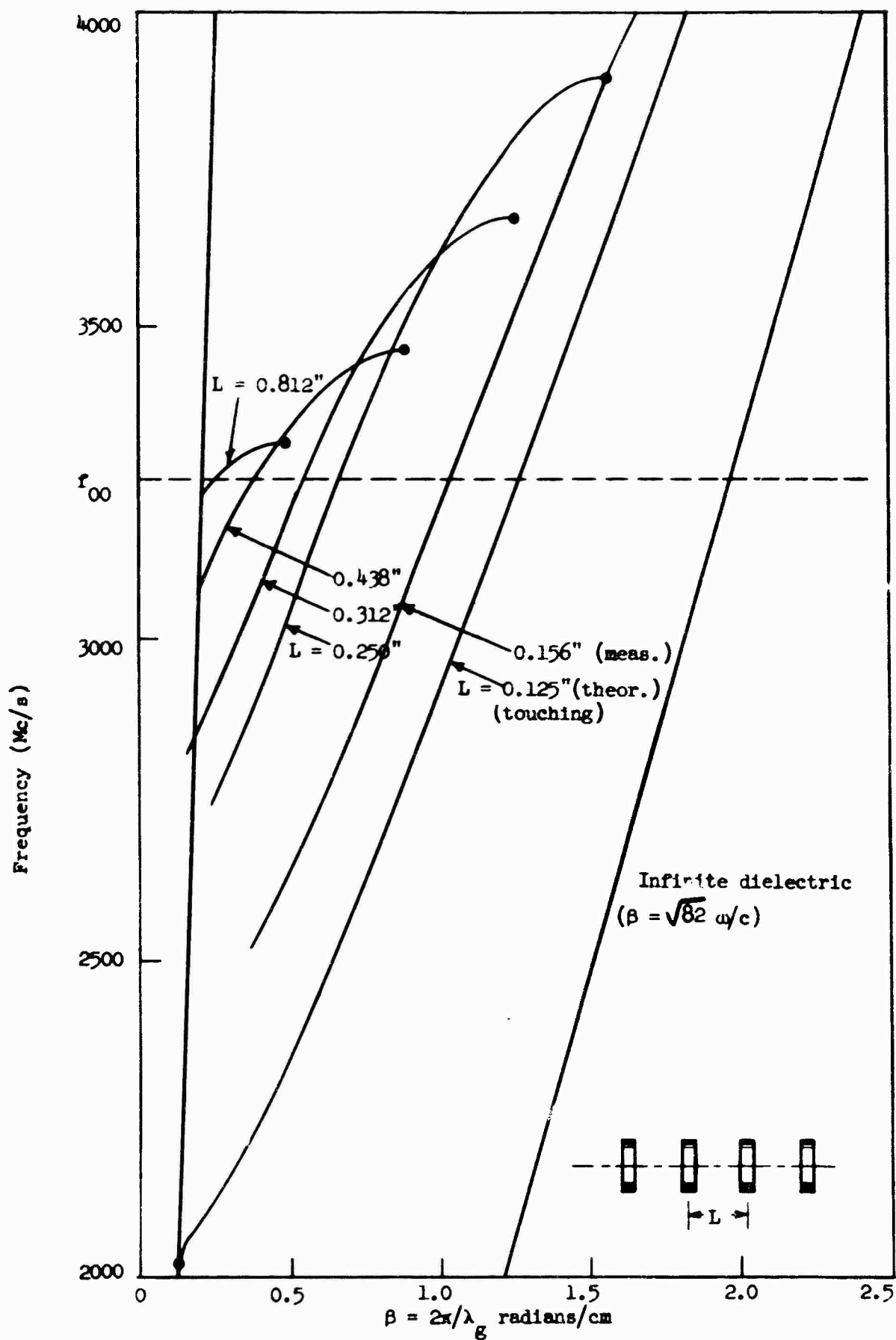


FIG. 16--Propagation characteristics of slow waves on an unshielded array of rutile disks for various spacings.

3. OSCILLATION SUPPRESSION IN TWT'S

(D. K. Winslow,* A. Bahr, R. Wilson)

A. INTRODUCTION

The objective of this study is to suppress the various types of oscillations that can occur in a periodic structure when it is excited by an electron beam (as in high-power traveling-wave tubes) without introducing excessive attenuation into the operating frequency band. Of particular interest are the pulse-edge (π -point) oscillations which are inherently possible in any TWT which utilizes certain types of periodic structures. The technique which is being applied to this problem is that of selectively coupling the periodic structure to an external, lossless, uniform waveguide. The selectivity is obtained by properly adjusting the phase and attenuation characteristics of the waveguide. The structure being studied in this case is the "centipede" structure, but this same technique could be applied to the particular oscillation problems of any other periodic structure such as the "cloverleaf" or the "long-slot."

B. DISCUSSION

Since the last reporting period, all the work on this project has been completed and a complete, comprehensive report has been written. The abstract of this report, RADC-TDR-172, follows:

"There are many factors involved in the design of a traveling-wave tube (TWT), the most important of which are gain, bandwidth, efficiency, and stability. The primary purpose of this study was to examine the question of stability in high-power TWT's which utilized coupled-cavity structures, both as to the concepts and theoretical description of the possible types of instabilities that can occur and as to the possible schemes for making the tube stable. Of the three types of oscillations which are possible in a pulsed, high-power TWT, it was the band-edge oscillations which were of primary interest.

* Project supervisor.

Two different theoretical approaches to the analysis of oscillation phenomena in coupled-cavity structures were examined. It is shown how the first of these, uniformly-coupled propagating-mode theory, may be applied consistently to such a periodic system. However, it is also shown that such a theory only applies within a passband and not at a circuit cutoff. For frequencies within a passband, then, particular three-coupled-mode solutions are given for a backward-wave oscillator and forward-wave amplifier which operate synchronously at the same frequency and which are coupled over part of their length to an external waveguide whose purpose it is to suppress the backward-wave oscillations. The results indicate (without considering the practical problems involved) that a substantial increase in start-oscillation length may be obtained with only a relatively small percentage decrease in forward-wave gain.

The second theoretical approach emphasized the coupled-cavity nature of the structure and is more appropriate for analyzing the oscillation phenomena which occur near the band-edge frequency. The system was analyzed in terms of individual cavity modes which are resonant at a particular cutoff frequency of the structure. The results of the analysis are expressed in terms of matrices whose elements are given in terms of easily measurable or calculable parameters. The theory gives an adequate description of the oscillation phenomena occurring near a cutoff and also predicts the same sort of backward-wave oscillations in the passband that are obtained from coupled propagating-mode theory. Also, the theory is general enough to apply to a "tapered" structure.

A comparison with the general coupled-cavity theory shows that the results of a simple application of Wessel-Berg's Monotron theory are adequate for estimating the minimum start-oscillation length of a nontapered structure at cutoff, but that they will always underestimate the starting length by a few percent. The coupled-cavity theory was also used to evaluate the effect of nonresonant slot coupling between the cavities and an external waveguide for frequencies both in the passband and near a circuit cutoff.

Experimentally, the frequency and voltage of the π -point band-edge oscillations occurring in the "centipede" structure were measured on the

"electron stick" for various structure lengths, and good qualitative agreement with the coupled-cavity theory was obtained. To some extent, quantitative agreement was also obtained.

"Three suppression schemes were examined on the electron stick, all of which use resonant, radiating slots to provide loss in a narrow frequency range near the band-edge of interest. The difference between the schemes lies in the type of external environment into which the slots radiate, which in this case takes the form of a lossless, terminated waveguide, a lossy waveguide, and pure lossy material. All of these schemes give increases in start-oscillation length of 30% or more, with almost no effect on the small-signal gain in the passband except near the band-edge. The lossless waveguide was found to give the greatest effect."

4. EXTENDED-INTERACTION KLYSTRONS

(M. Chodorow, * A. Karp, B. Kulke)

A. INTRODUCTION

The primary purpose of this project is to further investigate the maximum gain-bandwidth product and conversion efficiency as achieved in an extended-interaction klystron, with cavities consisting of resonated sections of slow-wave structure. The current, and final, phase of this work is the evaluation, by means of the electron stick, of a three-cavity L-band tube which was described in the last Quarterly Report. In this device, broadband modulation of the electron beam is simulated with input and intermediate cavities containing tunable resonated sections of ring-bar structure. The length of the output cavity can be changed, in half-wavelength increments, from one to five resonant half-wavelengths of its component ring-bar structure, and the loading can be adjusted by changing the terminal conditions on the couplers attached to both ends of the output resonator.

B. DISCUSSION

Assembly of the experimental three-cavity L-band tube has been completed, and beam tests of this device are in progress. The parameters of primary interest, i.e., saturation bandwidth and efficiency, will be evaluated for different lengths and loading conditions of the output cavity, and for different beam velocities; the object is to achieve an empirical optimization of these parameters. Small-signal gain and bandwidth will also be evaluated and compared to the linear theory. It is expected that the small-signal results, in the absence of a simple model which could represent the large-signal behavior, may be helpful in arriving at an optimum combination of parameters even for saturated-beam conditions.

* Project supervisor.

5. TRANSVERSE-WAVE STUDIES

(T. Wessel-Berg, B. Hoeks)

A. INTRODUCTION

The objective of this project is to study a possible approach to broadband high-powered amplifiers which involves interaction between an electron beam and a circuit in the presence of an axial dc magnetic field. This amplification mechanism depends on interaction between the transverse motion of the beam with transverse electric fields. Examples of such interaction are the Adler low-noise quadrupole amplifier, and the so-called fast-wave tubes where a rotating electron beam is interacting with an ordinary fast electromagnetic wave in a smooth waveguide. In the first case this type of interaction was used for low-noise amplifiers; in the second case, for very high frequency amplifiers. There are many possible variations of this kind of interaction, however, which would be appropriate to any frequency range and not merely for low noise.

B. SPACE-CHARGE WAVES IN AN ACCELERATED PARALLEL-FLOW ELECTRON BEAM IN A CONSTANT MAGNETIC FIELD

In a previous report we had indicated that use would be made of vector and scalar potentials. We have found that analytical solutions of these expressions can be obtained only in the case of a thin beam. With

$$E_r(r, \theta, z, t) = 1/2(E_- + E_+) \quad (1)$$

and

$$E_\theta(r, \theta, z, t) = 1/2j(E_- - E_+) ,$$

the solutions may be represented by

$$\begin{aligned} E_{\pm} &= E_{\pm}^{(1)} + E_{\pm}^{(2)} \\ E_z &= E_z^{(1)} + E_z^{(2)} , \end{aligned}$$

* Project supervisor.

and

$$\rho = \rho^{(1)} + \rho^{(2)}, \quad (2)$$

where the two partial solutions are given by

$$\begin{aligned} E_-^{(1)} &= e^{j\omega t} \sum_{n=1}^{\infty} 2n r^{n-1} \hat{E}_{-n}^{(1)}(z) e^{jn\theta} \\ E_+^{(1)} &\approx 0 \\ E_z^{(1)} &= e^{j\omega t} \sum_{n=1}^{\infty} r^n \hat{E}_{zn}^{(1)}(z) e^{jn\theta} \\ \rho^{(1)} &= e^{j\omega t} \sum_{n=1}^{\infty} r^n \hat{\rho}_n^{(1)}(z) e^{jn\theta}, \end{aligned} \quad (3)$$

and

$$\begin{aligned} E_-^{(2)} &\approx 0 \\ E_+^{(2)} &= e^{j\omega t} \sum_{n=1}^{\infty} 2n r^{n-1} \hat{E}_{+n}^{(2)}(z) e^{-jn\theta} \\ E_z^{(2)} &= e^{j\omega t} \sum_{n=1}^{\infty} r^n \hat{E}_{zn}^{(2)}(z) e^{-jn\theta} \\ \rho^{(2)} &= e^{j\omega t} \sum_{n=1}^{\infty} r^n \hat{\rho}_n^{(2)}(z) e^{-jn\theta}. \end{aligned} \quad (4)$$

In the following analysis, only the partial solutions (3) will be considered, since the final results can be easily generalized to the solutions (4) without additional computations. The potentials have been evaluated for an

infinitely long beam, while taking into account the effects of retardation. Insertion of these potentials into the force equation yields the second-order differential system

$$\begin{aligned} \left(j\omega + v_0 \frac{d}{dz} \right) \hat{S}_{-m}^{(1)} &= \hat{v}_{-m}^{(1)} , \\ \left[j(\omega - \omega_c) + v_0 \frac{d}{dz} \right] \hat{v}_{-m}^{(1)} &= -\frac{1}{2} \frac{\omega_p^2}{\omega_c} \left(1 - \frac{v_0^2}{c^2} \right) \hat{S}_{-m}^{(1)} \end{aligned} \quad (5)$$

where

$$\hat{S}_{-m}^{(1)}(z) = \text{displacement,}$$

$$\hat{v}_{-m}^{(1)}(z) = \text{velocity,}$$

$$c = \text{speed of light,}$$

$$\omega = \text{signal frequency,}$$

$$\omega_c = \text{cyclotron frequency,}$$

$$\omega_p(z) = \text{plasma frequency, and}$$

$$v_0(z) = \text{dc beam velocity.}$$

The longitudinal components can be obtained from (5) and

$$\left(j\omega + v_0 \frac{d}{dz} \right) \left(v_0 \hat{v}_{zm}^{(1)} \right) = -\frac{1}{2} v_0 \left(\frac{d}{dz} + \frac{j\omega v_0}{c^2} \right) \left(\omega_p^2 \hat{S}_{-m}^{(1)} \right) ,$$

$$\frac{d\hat{J}_{zm}^{(1)}}{dz} = j\omega_p^2 \hat{S}_{-m}^{(1)} ,$$

and

$$J_{zm}^{(1)} = \rho_0 v_{zm}^{(1)} + \rho_m^{(1)} v_0 . \quad (6)$$

Since the nonrelativistic force equations are considered, the term v_0^2/c^2 in (5), which would correspond to the $v_0 \times B$ term, will be omitted. Equations (5) permit an exact solution for $\omega_c = 0$. At the present time we are considering first order WKB as well as asymptotic series solutions for both large and small values of the product $\omega_c Z^{1/3}$, where Z is the spatial distance from the potential minimum at the cathode.

6. NONPERIODIC DIELECTRIC TRAVELING-WAVE TUBES

(A. Karp, * T. Fukunaga)

A. INTRODUCTION

This project has been concerned with the potentialities of high-voltage (order of 100 kV) traveling-wave and related (e.g., distributed-interaction klystron) tubes whose rf structures are simply uniform, homogeneous dielectric sleeves inside a copper shell. The high voltage corresponds to dielectric constants less than 10 in such tube designs and when combined with modest bandwidths (not over 30%) close to the TM_{01}^0 -mode cutoff, the same high interaction impedance and gain obtainable with periodic structures is to be expected. In addition, the possibility of using high-thermal-conductivity beryllia ceramic as the dielectric should permit exceptionally high power capacity at a given wavelength. The special advantage of the nonperiodic structure, however, as compared with periodic structures, is the freedom from spurious oscillations due to π -modes, backward space-harmonic waves and nearby extra passbands.

B. DISCUSSION

This project, which was committed to tests using the electron stick, is discontinued due to final dissatisfaction with a wire helix as a beam-tunnel lining of the proposed structure. Some recommendations will be set down, for the record, as the advantages of a nonperiodic structure remain very promising, providing some suitable beam-tunnel lining can be developed. A uniform resistance film is a possibility, with a compromise made with regard to absorption of desired TM_{01}^0 waves by the film. A combination of resistance film and wire helix would be attractive if the film conductivity needed to suppress helix oscillations could be less than that needed to conduct intercepted beam current in the absence of the helix.

* Project supervisor

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13 ABSTRACT <p>Current work being accomplished under Contract AF30(602)-2575 is reviewed. Included topics are listed below:</p> <p>I. CENTIPEDE TWT - Current results of theory and experiment are presented.</p> <p>II. PERIODIC CIRCUIT STUDIES - A. Modifications of existing circuits and new circuits for high power TWT's for improvement of bandwidth, impedance, and stability are investigated.</p> <p>B. Evaluation of an unshielded periodic array of small dielectric resonators as a positive-dispersion slow wave structure providing an axial H-field is presented.</p> <p>III. OSCILLATION SUPPRESSION IN TWT's - An abstract from a report on TWT oscillation suppression (pulse edge) by means of coupling to an external lossless waveguide is given.</p> <p>IV. EXTENDED INTERACTION KLYSTRONS - Assembly of an experimental three-cavity tube has been completed.</p> <p>V. TRANSVERSE WAVE STUDIES - Investigation of transverse wave propagation on an accelerated stream is continuing.</p> <p>VI. NONPERIODIC DIELECTRIC TRAVELING WAVE TUBES - This work has been discontinued. A statement of recommendations is contained herein.</p>			

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